Validating Lidar Depolarization Calibration Using Solar Radiation Scattered By Ice Clouds

Zhaoyan Liu, Matthew McGill, Yongxiang Hu, Chris A. Hostetler, Mark Vaughan and David Winker

***Abstract*—This letter proposes the use of solar background radiation scattered by ice clouds for validating space lidar depolarization calibration. The method takes advantage of the fact that the background light scattered by ice clouds is almost entirely unpolarized. The theory is examined with Cloud Physics Lidar (CPL) background light measurements.**

***Index Terms*—Depolarization Measurement, Calibration, Solar Radiation, Spaceborne Lidar.**

I. Introduction

The lidar to be flown on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) [1] mission improves upon its predecessor, the Lidar In-space Technology Experiment (LITE) [2], by adding the ability to measure profiles of volume depolarization ratios at 532 nm. Depolarization ratios provide useful information about the shape of scattering particles. Linearly polarized light backscattered from non-spherical particles depolarizes, whereas, when multiple scattering can be ignored, the backscatter from spherical particles produces no depolarization. Depolarization ratios are used for discriminating ice *crystals from water droplets* [3], [4], and can also be used for discriminating mineral aerosols (irregular particles) from other types of aerosols having spherical particles [5], [6]. In the analysis of the CALIPSO lidar data, depolarization measurements play an important role in cloud/aerosol discrimination [7], cloud phase determination [8] and aerosol type identification [9]. Deriving accurate depolarization ratios requires knowledge of the depolarization gain ratio, which characterizes the relative gain between the perpendicular and parallel channels of the lidar receiver. An accurate depolarization gain ratio is especially important for the CALIPSO measurements, as the total backscatter at 532 nm (i.e., the gain-ratio-weighted sum of the polarization components) is a critical component in deriving the 1064 nm lidar system constant [10]. This study proposes a method for validating CALIPSO's internal calibration of the depolarization gain ratio.

The depolarization gain ratio can be determined by inserting a half-wave plate with its optical axis aligned at 22.5° to the transmitted laser polarization direction into the optical path of the transmitter [11] or the receiver [12]. In either case, the polarization state of the backscattered light will be rotated by 45° with respect to the receiver's polarization beam splitter, and thus the detectors will be exposed *to signals of equal magnitude, irrespective of the scattering* source. The depolarization gain ratio is simply the ratio of the output signals of the two channels. The gain ratio can also be determined by comparing the intensities of diffused, unpolarized light received at both parallel and perpendicular channels [6],[13]. The unpolarized light provides equal optical power to the two polarization channels, and the gain ratio is once again determined by taking the ratio of the output signals in the two channels. The CALIPSO lidar employs a spatial pseudo-depolarizer to generate the unpolarized signal necessary for the gain ratio calibration procedure [14]. A Polarization Gain Ratio Operation mode is planned, and calibration measurements will be made periodically throughout the mission.

In this study, we propose the use of solar background radiation scattered from ice clouds for validation of the depolarization gain ratio. The background light received by lidar is the sunlight scattered by the land and ocean surfaces as well as by clouds, aerosols and molecules in the atmosphere. Because the background light scattered by ice clouds is essentially unpolarized, the difference in backscatter intensity between the parallel and perpendicular channels ought therefore to be minimal.

The airborne lidar data set acquired by the Cloud Physics Lidar (CPL) [12] during the THORPEX-PTOST campaign in 2003 provides the opportunity for evaluating the proposed validation method. This paper presents a simplified theoretical explanation of the validation method and illustrates the technique using CPL data.

II. Theoretical Basis

For this study we assume that we can identify a subset of lidar measurements of the ambient background solar radiation for which there is little, if any, polarization of the

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signal. For water clouds and ocean surfaces, a difference between the parallel and perpendicular components exists when single scattering dominates the background returns. For single scattering of sunlight from cloud droplets [8]

$$I_\perp = 0.5\sigma_{sca} I_0 [P_{11}(\Theta) + P_{12}(\Theta)\cos(2\Delta\phi)]$$
$$I_\parallel = 0.5\sigma_{sca} I_0 [P_{11}(\Theta) - P_{12}(\Theta)\cos(2\Delta\phi)] \quad (1)$$

where I_0, $I_\parallel$ and $I_\perp$ are the intensity of incident light and the parallel and perpendicular components of the scattered light, respectively, and σ_{sca} is the scattering cross section of the cloud. P_{11} and P_{12} are components of the scattering phase matrix. $\Delta\phi$ is the angle between the planes formed by (a) the solar incidence and the nadir-pointing direction of the airplane, and (b) and the polarization direction of the laser and the nadir-pointing direction of the airplane. The scattering angle $\Theta = 90° + \alpha$, where α is the solar elevation angle.

The polarization components for the single scattering of sunlight from the ocean surface are given by

$$I_\perp = 0.5[(I_{\perp 0} + I_{\parallel 0}) + (I_{\perp 0} - I_{\parallel 0})\cos(2\Delta\phi)]$$
$$I_\parallel = 0.5[(I_{\perp 0} + I_{\parallel 0}) - (I_{\perp 0} - I_{\parallel 0})\cos(2\Delta\phi)] \quad (2)$$

where the perpendicular and parallel polarization components for $\Delta\phi = 0$ are given by

$$I_{\perp 0} = c I_0 \sin^2(i-r)/\sin^2(i+r)$$
$$I_{\parallel 0} = c I_0 \tan^2(i-r)/\tan^2(i+r). \quad (3)$$

i and r are the incident and refraction angles relative to a surface wave that follows the Cox-Munk distribution. For ocean surface measurements, the background signals are dominated by the specular reflection of background light from those sunny-side slant surfaces having a slant angle of $45° + 0.5\alpha$. In equation (3), the solar incident angle for those slant plane surfaces is $i = 0.5 \times (90° - \alpha)$. c is a wind-driven wave slope probability function determined by wind speed and direction. For the ocean surface scattering, the parameter c cancels out in $I_\perp / I_\parallel$, and thus the ratio relevant to this study, $I_\perp / I_\parallel$, does not depend on the ocean surface wind conditions.

Figures 1 and 2 show results of single scattering calculations for ice clouds with aggregate particle phase matrix [16] (upper panels of Figure 1), water clouds (lower panels of Figure 1), and the ocean surface (Figure 2) for which the solar illumination direction is parallel to laser polarization direction ($\Delta\phi$=0).

From Figures (1) and (2) it is clear that $I_\perp / I_\parallel$ varies with the sun elevation angle α for both water clouds and ocean surface, while difference between $I_\perp$ and $I_\parallel$ is small for ice clouds ($I_\perp / I_\parallel \approx 1$).

The scattering of solar radiation from certain ice cloud particles, such as horizontally oriented ice plates, can be polarized. The polarization of background light is a result of light scattering (either internally or externally) from a flat surface. Fortunately, the depolarization ratios measured from these clouds are quite low, while the corresponding attenuated backscatter signals are large [15]. As a result, these episodes can be easily identified and removed from consideration.

Multiple scattering will further depolarize the background signals, hence the background light emitted by multiple scattering media such as dense ice clouds is even less polarized than that emanating from optically thin ice clouds.

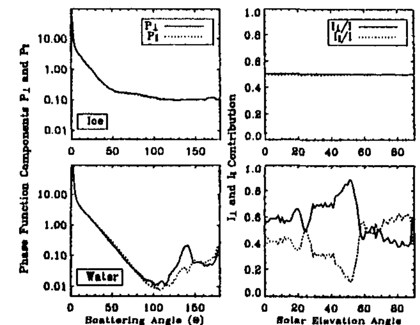

Figure 1 Polarization components for ice (upper panels) and water (lower panels) clouds.

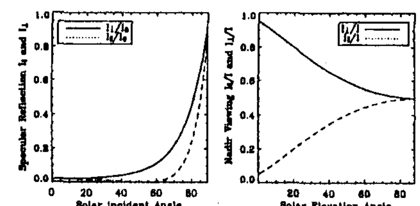

Figure 2 Polarization components from ocean surface; the lidar is assumed to be pointing at nadir.

The scattering characteristics shown here suggest that the solar background radiation from ice clouds can be used as a light source to validate the calibration of space lidar depolarization measurements.

III. Case Study with CPL Data

The Cloud Physics Lidar (CPL) is an airborne polarization-sensitive three-wavelength system developed at NASA's Goddard Space Flight Center [12]. CPL measures total backscatter profiles at 355 nm and 532 nm, and makes

independent measurements of the parallel and perpendicular components at 1064 nm. Observations acquired during the THORPEX-PTOST 2003 campaign in Honolulu, Hawaii are used to test the validity of the method. Upper panel of Figure 3 is an example of 532 nm attenuated backscatter profile acquired on February 22, 2003. The middle panel of Figure 3 is the perpendicular-to-parallel ratio of solar background radiation at 1064 nm and the lowest panel is the perpendicular component at 1064 nm. The scattered solar background radiation for each profile is derived from the signals below the surface where laser beam is totally attenuated and the background solar radiation signal dominates. The CPL detector noise is negligibly small compared with the solar background radiation during daytime. The CALIPSO lidar cloud and aerosol discrimination algorithm [7] has been applied to classify scene types (ice cloud, water cloud and cloud-free). Colors in the middle and lower panels denote different scene types: cloud-free lidar profiles are shown in red, profiles containing water clouds in blue, and those containing ice clouds in green. When a cloud layer is identified, its layer averaged total depolarization ratio, $\overline{\delta}$, is compared to a threshold value to determine its ice-water phase. Those clouds for which $\overline{\delta}$ exceeds the threshold are interpreted as ice; all others are classified as being water. A relatively high threshold of 20% has been chosen in this study to ensure that most mixed-phase clouds and those ice clouds containing horizontally oriented crystals are screened out, because the scattered solar background radiation from these clouds is not guaranteed to be sufficiently unpolarized. Optically thin ice clouds with very low scattering ratio and low lidar depolarization ratio are also excluded, because solar scattering from water clouds or ocean surface underneath these thin clouds dominates the background signal.

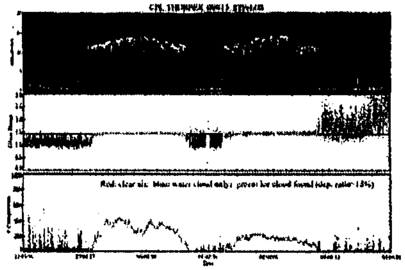

Figure 3: Attenuated backscatter at 532 nm (upper panel), perpendicular-to-parallel component ratio S/P (middle panel), and parallel component P (lower panel).

The base of the cirrus anvil shown in Figure 1 (upper panel) lies above 10 km. The aircraft made four passes over this layer. Although the sun elevation angle changed by about 50° during this 4-hour flight, the perpendicular-to-parallel ratio of the scattered solar radiation from the cirrus layer remains almost constant throughout the entire layer and is consistent with the value (solid line in the middle panel) determined with the half-wave plate method [12] for this flight. This demonstrates that the scattered solar radiation from cirrus layer is not polarized, regardless of sun elevation angle. Deviations are seen at the edges of the cirrus cloud where the cloud layer is transmissive and the polarization is affected by the lower water clouds and ocean surface.

On the other hand, the scattering of solar radiation from both water clouds and the ocean surface is polarized and the ratios measured depend on the sun elevation angle. This is consistent with theory. Both the theory and observation indicate that water clouds and water surface polarize the scattered sunlight. Similar results were obtained for all ten flights carried out during the campaign.

IV. Proposed Approaches

Based on the theoretical studies and CPL data analysis, we propose two approaches for validating CALIPSO's lidar depolarization calibration. Approach 1 is a linear-fit method. Figure 4(a) presents scatter plots of perpendicular component vs. parallel component for all background solar signals of Fig. 3(a). Figure 4(b) is for cirrus only. When a linear fit is applied to these points, the slope of the fitted line is the gain ratio of the two channels. The slopes for both Figure 4(a) and 4(b) are very close and consistent with the gain ratio determined by the half-wave plate method (1.443). For approximately half of the profiles in this flight, the background is dominated by ocean surfaces (i.e., cloud-free conditions). Since the fitting process is strongly influenced by the high levels of background solar radiation scattered by the anvil clouds, the two slopes from 4(a) and 4(b) are almost identical.

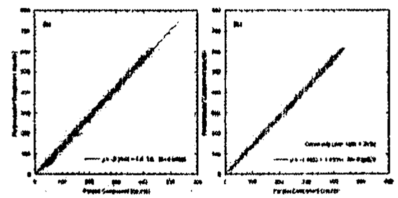

Figure 4: Scatter plots for all cases (a) and for the ice-cloud only cases (b) with linearly fitted line, for the flight on February 22 as shown in Fig. 3.

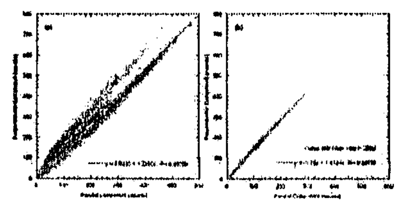

Figure 5: Same as Fig. 4 but for the flight on February 19.

The linear-fit based slop approach that uses all scattered solar signals similar to that shown in Fig. 4(a) has been used to validate the CPL gain ratio calibration. Repeated CPL observations show that this method is quite reliable when ice clouds are the dominant scattering media.

When scattering is dominated by a polarizing medium such as thick water clouds and/or an ocean surface with strong winds, large biases may be introduced into the fitting process. An example is given in Fig.5. The plots are same as Fig. 4, using data from the February 19, 2003 flight. Compared to Fig. 4(a), a much larger spread of data points is seen in Fig. 5(a). A substantially better correlation is seen when fitting the ice-cloud-only data points, as shown in Fig. 5(b). The two slopes (gain ratios) differ by ~7%. Approach 2, which we suggest for use by CALIPSO, is based on fitting ice-cloud-only data points as shown in Fig. 4(b) or 5(b).

This technique can also be used as a diagnostic method to check the stability of the CALIPSO gain ratio calibration. The on-board method will be applied only periodically, and requires the insertion of the spatial pseudo-depolarizer into the optical path. By contrast, the approach outlined here can be applied to the daytime part of each CALIPSO orbit without commanding the insertion of additional on-board optics.

The lidar depolarization ratio is used to select the appropriate data for the gain ratio calibration. Figure 6 presents scatter plots of data points selected with threshold values of lidar depolarization ratio of 10% (a) and 20% (b) from all ten CPL flights conducted during the THORPEX-PTOST 2003 campaign. It is clearly shown that the outlier data points that arise from solar radiation scattered partly from optically thin ice clouds and partly from ocean surface is effectively screened out by using the higher threshold value of the depolarization ratio.

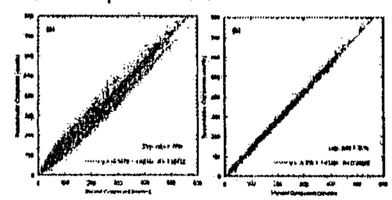

Figure 6 Scatter plots of data points selected with depolarization ratio great than 10% (a) and 20% (b) from all ten flights data acquired by CPL during the THORPEX_PTOST 2003 campaign.

Approach 2 is proposed for CALIPSO. This technique selects a high dense cirrus anvil like the one shown in Fig. 3. The ratio of perpendicular to parallel components is plotted as in the middle panel of Fig. 3. The depolarization gain ratio can then be derived from the mean value of the flattest part of the curve. The flatness of the curve can be used as a metric to select an appropriate ice cloud for analysis.

We note too that although only the background light scattered by ice clouds is used to validate or generate the depolarization gain ratio, once generated the calibration constant is then valid regardless of the scattering source, and can be applied to the lidar measurements over water clouds, aerosols, etc.

V. Conclusion

Using the sunlight scattered from ice clouds, we can validate the internal calibration of CALIPSO lidar depolarization gain ratio. This method is based on the fact that the background sunlight scattered by ice clouds is largely unpolarized, while the background sunlight scattered by water clouds and ocean surface can be polarized.

This validation method was tested on Cloud Physics Lidar data acquired during the THRORPEX-PTOST campaign. The results show that the CPL depolarization gain ratio is consistent in general with theory. Based on the theoretical and CPL data analysis, two approaches are proposed for the validation of CALIPSO depolarization calibration. Both approaches assume unpolarized solar background radiation scattered from ice clouds. A relatively high depolarization ratio threshold is used as a discriminator to insure that only ice clouds with unpolarized background light are selected, while background measurements over water clouds and the polarizing ice clouds such as horizontally oriented ice plates are excluded.

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